GENESIS, CLASSIFICATION, AND LANDUSE POTENTIAL

OF SOME MOLLISOLS OF MAUI, HAWAII

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I. INTRODUCTION

There have been very few studies conducted on tropical Mollisols because of their small total land area. Their good physical and chemical properties, however, make them important agricultural soils. In this study, an attempt will be made to analyze some of the important aspects of their formation, their contribution to soil properties, and the characteristics of these soils in relation to land use.

The area of study is on the island of Maui, the second largest of the Hawaiian Islands, with a total land area of 1,885 km^2. The island lies betweeen 20° 40' and 21° 2' north latitude and 156° 0' to 156° 40' west longitude. The study area more specifically includes the western slopes of Mt. Haleakala on East Maui, where the elevation ranges from near sea level to about 800 m above sea level.

The Mollisols of Maui, like most other Mollisols, have good physical properties and high natural fertility. Their suitability for crop production, however, is limited by the lack of moisture, as they occur on the Isthmus between East Maui and West Maui mountains and in the rainshadow of Mt. Haleakala. Much of the lowland areas are in grasslands with xerophytic shrubs or in irrigated sugarcane, while the uplands are devoted to irrigated vegetable or floral crops.

The objectives of this study are:

1. Study the influence of soil forming factors associated with some of the Mollisols on East Maui.

2. Characterize and classify the Mollisols which occur on the western slopes of Mt. Haleakala.

3. Assess the landuse potential of the Mollisols for specified use.

II. LITERATURE REVIEW

2.1 Soil Forming Processes and Factors

The properties and characteristics of the soil at any given place are determined by soil forming processes that result from:

(1) the past and present climate associated with the soil;

(2) the physical and mineralogical composition of the parent material;

(3) variations in local and surrounding topography;

(4) the kinds and number of plants and animals that live in and on the soil;

(5) the length of time the processes of soil formation have acted on the parent material.

Soil formation results from a combination of processes acting in different proportions and intensities at different times on the soil landscape. In addition, the balance among individual processes in a given combination results in the differentiating properties that are unique to different soils. According to Fenton (1983) the processes of soil formation include additions, removals, translocations, and transformations. There is, furthermore, a strong interdependence among soil forming factors and soil characteristics such as mineralogy, texture, structure, and color could be a reflection of climate, biotic, and topographic factors operating on the parent material as a function of time.

2.1.1 Climate and Soil

Climate is one of the soil forming factors that have been recognized to have a direct bearing on soil formation. Temperature and rainfall affect the kind and amount of vegetation in an area. Organic matter accumulation is higher in cooler climates and its decomposition is faster in warmer climates. Precipitation affects clay movement and the amount of leaching in the soil. Warmer climates, along with high precipitation, favor more rapid weathering than cooler temperatures and scanty rainfall. The intensity of physical, chemical, and biological weathering is affected by combinations of effective temperature and precipitation.

Climate affects soil formation through its influence on weathering, pedogenesis, geomorphic processes, organic matter production and decomposition, and leaching. Climate directly affects soil formation through the effects of rainfall, wind, and changes in temperature. According to Simonson (1962), rainwater moving through the soil carries with it nutrients, organic matter, and clay from the surface to the subsoil or underlying material. Rainfall also influences the amount of leaching of nutrients and salts from the soil profile according to the downward movement of water.

The indirect effects of climate are manifested through the amount and kind of vegetation and animal life that is sustained. Favorable temperature and moisture conditions result in increased biological activity, accumulation of organic matter and darkening of the surface due to decomposition of vegetation. On the other hand, lack of moisture accompanied by high temperatures results in slow weathering of the parent material, slow leaching, and minimal eluviation and illuviation. A dry hot climate also results in a sparse plant cover and rapid decomposition of organic residues, resulting in little accumulation of organic matter.

The climate under which a soil has accumulated is not necessarily the climate that has existed since accumulation. There are evidences of climatic change preserved in many parts of the world including Hawaii (Selling, 1948; Ruhe, 1964; Porter, 1979; and Porter et al., 1983). The rates of soil formation would have increased when climatic conditions were optimal and slowed down when conditions were suboptimal.

In order to interpret some of the observed soil characteristics, which cannot be attributed to the present prevailing conditions, it is necessary to make inferences from the established history of some of the landscapes in Hawaii, for which the past climates have been established. In this way, reasonable extrapolations can be made for the adjoining areas. Such studies have been conducted on the island of Oahu (Ruhe, 1964, 1975). The paleoclimate studies of Hawaii indicate a much wetter climate as supported by evidences of fossil vegetation of the Illinoian glacial period (Selling, 1948).

2.1.2 Topography and Soil

The influence of topography on the distribution of soils on landscapes has been determined both from the pedologic and geomorphic point of view. The Soil Survey Staff (1984) defined topography as the relative positions and elevations of the natural or manmade features of an area that describe the configuration of its surface, and relief as the elevations or inequalities of a landsurface, considered collectively. The context in which relief has been used qualifies it as a component of topography.

Topography affects the distribution of soils on a landscape through its effects on drainage, erosion, soil depth and penetration of water into the soil. Elevation and slope position on the landscape are important elements of topography. Some of the differences in soils that vary with topography are through its effects on climate.

In a toposequence, soil properties are related to the gradient of the slope as well as to the particular position of the soil on the slope. Each soil along a slope bears a distinct relationship to the soil above and below it for a variety of geomorphological, geological, and pedologic reasons. According to Birkeland (1984), slope steepness affects soil properties through its effects on runoff and erosion. Low lying areas are more likely to be areas of accumulation of runoff water and sediment derived from the surrounding higher areas. Soils on nearly level topography tend to be thicker than those on slopes. Buol et al. (1980) explain this phenomenon to be a result of either geological erosion of soil material on the surface or losses by runoff, or both, occurring on the slope.

2.1.3 Vegetation and Soil

Vegetation provides cover and protects soil from intense weather, adds organic matter to the soil, improves the soil physical structure, and improves the water holding capacity of the soil, thus reducing runoff. Plant roots penetrate the earth's mantle and improve the permeability and aeration of the soil.

Cline (1955) recognized the intricacy of the relationship between soil and vegetation since plants grow in and on the soil. Changes in soil properties that take place during its development influence the kinds and amount of vegetation it can support. Also, a similarity in vegetation types is encountered in climatic zones occupied by a major group of soils. For example, soils with an aridic moisture regime can support only sparce plant communities, which in turn will produce less organic matter than areas with higher precipitation. It therefore becomes difficult to distinguish the effects of vegetation on soil, soil on vegetation, and climate on vegetation and soil. This relationships make vegetation both a dependent and independent factor of soil formation (Jenny, 1941).

Organic matter production and distribution, soil structure, tilth, and nutrient recycling, are some of the soil properties and processes that can be directly linked to vegetation. Fenton (1985), observed that organic matter distribution with depth varies with vegetation type. Under grassland, the A horizons are thicker, and the organic matter content remains higher with depth than under forest vegetation because of the higher biomass production under grass vegetation.

2.1.4 Time and Soil

Soil formation begins when rock is exposed on the earth's surface. As soil formation progresses, characteristic layers or horizons develop. Generally, the greater the number of horizons and the greater their thickness and distinctness, the more mature is the soil. The length of time required for a soil to develop depends on the parent material and the intensity of the soil forming factors.

There is a strong interdependence between time and the other soil forming factors. According to Brady (1984), the time it takes for a horizon to develop is strongly related to the parent material, the climate, and the vegetation. Paramananthan and Eswaran (1980), in their work on Oxisol morphology, indicated that while the weatherability of parent materials strongly influenced the morphology of Oxisols, soil formation also proceeded for a long time to produce the characteristics that are observed in these soils.

Ruhe *et al.* (1965), and Ruhe (1975), determined the approximate ages of the different stands of the sea and demonstrated the relationship between soils, parent materials, time, and climate on various geomorphic surfaces in the Waipahu-Ewa area of Oahu. According to Ruhe (1975), the one factor of soil formation that is least affected by time is parent material, while climate, vegetation, and topography may change with time. As a result, soils may differ from surface to surface. Some of the soil characteristics that are usually observed to determine the relative ages of soils are eluviation, formation of clay films, weathering of clay minerals, and transformation of one clay mineral to another. Solum thickness, thickness of the B horizon, and clay content of the B horizon have also been determined to be characteristics that can be used in evaluating relative ages of soils (Birkeland, 1984).

2.1.5 Parent Material and Soil

The nature of the soil is strongly influenced by the character of the parent material, particularly by its mineralogy and texture, because they affect the various physical and chemical aspects of the soil forming environment.

There are basically two kinds of parent materials: The original geological parent material which decomposes to various products in place and the pre-weathered and transported deposits (Paramananthan and Eswaran, 1980).

Soils formed in different kinds of parent materials normally have distinctive features that are associated with the individual parent materials. Basalt parent rocks have a high base status and low quartz content. As a result, a soil formed in basalt parent materials tends to have high pH and fine textures. Volcanic ash parent materials have allophane, an amorphous aluminosilicate which complexes organic matter in the upper solum, and have a low bulk density. As a result, some of the features commonly associated with volcanic ash soils are intensely dark surfaces with high organic matter contents and high water holding capacity, (Buol et al., 1980).

According to Juang and Uehara (1968), soils in Hawaii are less often the direct end product of weathering of the basalt parent material and more often the result of saprolite differentiation or alluvium. This is supported by lack of vertical uniformity in soils as reported by Ruhe (1965), through evidences supplied by stone lines, a feature that is associated with erosion and deposition. Studies by Ruhe (1956) and Gerrard (1981) have shown that where stone lines occur there are evidences of erosion by running water and that stone lines point to the existence of former erosion surfaces. According to Ruhe (1956), stone lines also indicate that the soil may have developed from more than one kind of parent material. Gerrard (1981) reported that the material below the stone line is weathered from bedrock whereas the material above the stone line is transported sediment. He also pointed out that the material comprising the stone line could be transported from further upslope and could be made up of entirely different materials.

2.2 Geology of East Maui

Maui, like the rest of the Hawaiian islands, is almost entirely volcanic except for a narrow fringe along the coast, which is made up of sedimentary rocks. Another area which is not entirely volcanic is the isthmus, being made up mostly of alluvial deposits from the two mountains that make up the island.

Haleakala volcano makes up East Maui. The oldest rocks in East Maui are of the Honomanu volcanic series, the basalts that built the dome to an approximate height of 2600 m in relation to the present sea level, before they were completely covered by the Kula volcanic series basalts (Stearns and Macdonald, 1942).

The Honomanu lavas were mainly pahoehoe and aa flows composed of tholeiite, tholeiitic olivine basalt, and oceanite (Macdonald et al. 1983). According to Stearns and Macdonald (1942), the dome probably began erupting above sea level in Pliocene time.

The Kula lavas are more silicious and less permeable than the Honomanu basalts. They form the surface over most of the northwestern and southeastern segments of the mountain. The Kula lavas are predominantly aa and are mainly hawaiite, with some alkali olivine basalt and ankaramite. The Kula volcanic series is probably early and middle Pleistocene in age (Stearns and Macdonald, 1942).

The Kula lavas have been weathered and soils of various thicknesses have formed in them. Some of the soils are very deep. Towards the end of the Kula eruptions, volcanic activity became infrequent and stream erosion started to cut valleys around the mountain, especially on the northern and eastern windward side.

After a long period of erosion, lava flows of the Hana volcanic series with rocks similar to the Kula series but predominantly alkali olivine basalts and basaltic hawaiites flowed over the more silicious Kula rocks. They were predominantly aa with a few pahoehoe flows in places. The Hana lavas were erupted in late Pleistocene and Recent times, and they have limited areal extent on East Maui.

The East Maui volcano has emerged and submerged several times since the building of the volcano to the Recent time, and according to Stearns and Macdonald (1942), this has resulted in cutting of cliffs and benches into partly weathered lavas, deposition of alluvium, and cutting through of the streams into the alluvium. The rise and fall of sea level was due in part to the changes in the volume of ice on the continents during the glacial period, and this may have contributed to the change in climate (Price, 1983).

2.3 Central Concept of Mollisols

Mollisols are mineral soils that have a mollic epipedon (dark colored surface horizon), with greater than 50 percent base saturation as determined by the NH_4OAc method, or have a surface horizon that after mixing to a depth of 18 cm, meets all the requirements of a mollic epipedon except thickness (Soil Survey Staff, 1975). According to Fenton (1984), these requirements tend to restrict Mollisols to subhumid and semiarid regions where leaching of bases is slow but enough moisture is available for adequate additions of organic matter to meet the requirements. Grasslands have a higher biomass production annually than forests and higher cycling of cations. Grasslands hence, have a higher overall base saturation.

Organic matter distribution and decomposition in the soil reflect differences among different vegetative environments.

The organic matter requirements of Mollisols tend to restrict them to areas with vegetation that is dominantly grass. Short grasses characterize areas where there is a periodic available moisture deficit, a phenomenon that will affect the distribution of organic residues, their decomposition, and incorporation into the soil system.

Mollisols have characteristics associated with melanization, that is, the darkening of the soil by addition of organic matter in the presence of Ca-saturated or Ca-rich forms of humus. According to Smith (1965), this requires decomposition in the soil and not on the soil. Kononova (1975), determined that the factors that may tend to promote greater content of organic matter in soils under grasses relate to proccesses favoring production of humic acid. Products of this type have been determined to protect the humus from rapid incorporation into biological processes, thus favoring accumulation of organic matter in the soil. Additional factors that appear to be associated with the accumulation of organic matter in Mollisols are high exchange capacity, saturation with Ca, and an abundance of mineral colloids. Thus, Mollisols are expected to have high base saturation and abundant Ca.

III. MATERIALS AND METHODS

3.1 The Study Area

The study area is located on the western leeward slopes of Mt. Haleakala in East Maui. The elevation ranges from 37 m to about 800 m above sea level and the area lies within the rainshadow formed by Mt. Haleakala. A summary of the characteristics of the physical environment is given in Table 3.1.

The climate is characterized by a hot dry season and a warm moist season with limited amounts of erratic rainfall which comes as light and brief showers. Average annual precipitation of the area is 500 mm, and most of it comes between October and February. Near sea level, the rainfall is less than 250 mm, but the soils generally receive more rainfall as elevation increases. Sunshine is abundant throughout most of the year, with cloudy periods being limited to the rainy season. Relative humidity is quite high, around 60 to 70 percent in the dry season and between 70 and 80 percent during the wet season. The warmest month is August with an average temperature of 25^{o} C, and the coldest is February with 21^{o} C. These conditions give rise to soils with an ustic moisture regime which borders on aridic.

Xerophytic plants are widely scattered on the western slopes of Haleakala. Below 300-m elevation, where rainfall is less than 350 mm, the vegetation consists mainly of the introduced buffel grass (*Cenchrus cialaris*), koa haole (*Leucaena leucocephala*), and kiawe

Table 3.1 Physical Environment of The Mollisols of East Maui.

	Pedon 1	2	3	4	5	6
Sampled as	Waiakoa	Waiakoa	Keahua	Keahua	Keahua	Keahua
Location	Hashimoto Farm, Kihei	Sugar Field 412, Kihei	Pasture, Waiakoa	Otani Farm, Omaopio	Pulehu Exp. Farm, Pulehu	Nakamura Farm, Pulehu
Elev. (m)	37	189	366	503	640	732
MAR (mm)	250	360	380	480	480	560
MAT (^{o}C)	25	24	23	22	22	19
Slope (%)	2	1	6	8	9	12
Perm.	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Drainage	WD	WD	WD	WD	WD	WD

MAR = mean annual rainfall, MAT = mean annual temperature,
Perm. = permeability, WD = well drained.

(Prosopis chinensis). This area is mainly used for pasture and cattle production. Irrigated sugarcane is also widely grown. In cooler locations, above 500-m elevations, vegetables are extensively grown.

The area is situated on a sloping and moderately sloping landscape with an undulating surface and several rounded depressions. In places, it is choppy with steep slopes. There are several rills and gullies at high elevations which regroup towards the middle and toe slopes to form deep gulches. The soils lack uniformity on the surface, having variation in stoniness within very short horizontal distances. In general, the number and size of the stones on the soil surface appear to decrease with increasing elevation. The parent material of the soils is alluvium or residuum derived from basic igneous rocks.

Two soil series were mapped in the study area: The Waiakoa and the Keahua soil series (Foote et al., 1972). Both soils were classified as Torroxic Haplustolls, fine, kaolinitic, isohyperthermic. Six pedons were descibed, two in Waiakoa mapping units and four in Keahua mapping units. Descriptions of the soils are presented in Appendix I. Figure 3.1 shows the general distribution of the Mollisols on the island of Maui. Figure 3.2, on the other hand, delineates the areas of the Waiakoa and Keahua soils within the area of Mollisols on Figure 3.1.

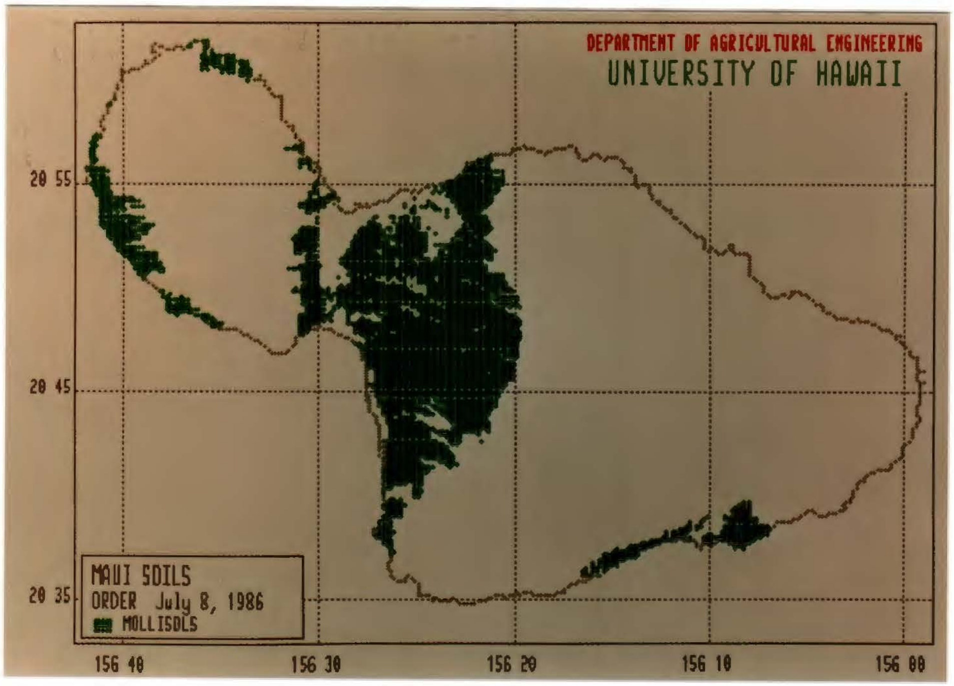

Figure 3.1 Distribution of Mollisols on The Island of Maui.

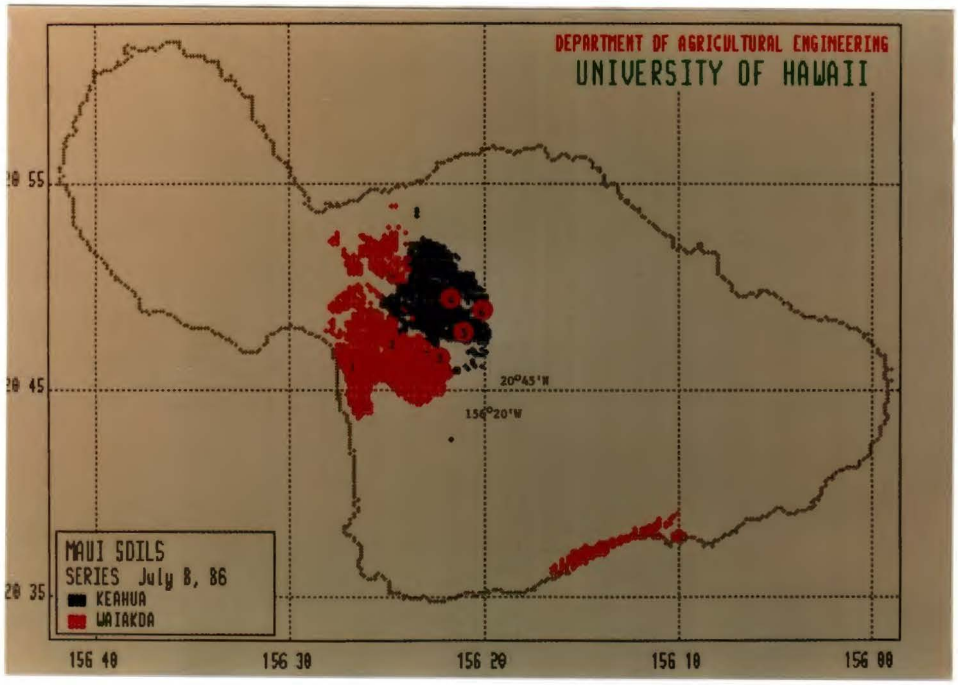

Figure 3.2 Waiakoa and Keahua Soil Series with Location of Sample Sites.

3.2 Analytical Methods

Sample collection and preparation, as well as the physical and chemical determinations were made according to "Procedures for Collecting Soil Samples and Methods of Analysis for Soil Survey" (SCS, USDA, 1984a). Samples for the analyses were first crushed and passed through a 2-mm sieve.

3.2.1 Physical Analyses

Bulk density was determined on samples that were equilibriated at 1/3-bar moisture and after oven-drying. Water content at 1/3- and 15-bars was obtained from natural clods and air-dried samples of <2mm, respectively. Water retention was then calculated from the difference between 1/3-bar and 15-bar tensions. For particle size distribution by the pipette method, organic matter was first destroyed with H_2O_2. The procedure was then modified by using either 50 or 100 ml of the dispersing agent instead of 10 ml to promote better dispersion.

3.2.2 Chemical Analyses

Organic C content was determined by acid dichromate digestion and total Nitrogen by ammonia steam distillation. Dithionite citrate extractable Fe, Al, and Mn were measured by atomic absorption. Extractable bases were also measured by atomic absorption in the extracts obtained by leaching the samples with NH_4OAc at pH 7.0. Extractable acidity was determined in $BaCl_2$-triethanolamine solution, then back-titrated with HCl. Cation exchange capacity (CEC) was expressed by the sum of extractable bases and extractable acidity and by the method of NH_4OAc-extraction at pH 7.0. Base saturation was then calculated on the basis of the two methods of CEC. The pH was measured in NaF, $CaCl_2$ and in water. For P retention, a procedure developed in New Zealand, using nitric vanadomolybdate acid reagent, was employed.

3.3 Land Evaluation

Assessment of the landuse potential was made by comparing the requirements of selected crops (cassava, jojoba, and tomatoes) with the soil and land characteristics of the study area. The general procedure of the Food and Agriculture Organization (FAO) of the United Nations was used (FAO, 1976).

IV RESULTS AND DISCUSSION

4.1 Morphological Properties

The morphological properties of the soils, as summarized from the soil descriptions in Appendix I, are presented in this section.

4.1.1 Soil Depth

Table 4.1 shows that the Ap horizon of the six pedons ranged in thickness from 26 to 31 cm, whether cultivated for crops or used for pasture. The solum thickness of Pedons 1 and 2 was 60 cm or less, while that of the other pedons ranged from 63 to over 150 cm.

Solum thickness is a function of the depth of weathering of the parent material, processes of erosion and deposition, and characteristics of the landscape and the local relief.

Although the effect of erosion and deposition must also be considered, the results indicate that there was more soil development in Pedons 3 through 6, which are associated with slightly higher rainfall distribution and hence more weathering of the parent material. At the same time, large amounts of rock fragments at the soil surface than in the subsoil may imply erosion and deposition. Landscape features may also affect soil depth. For example, it is likely that Pedon 6 which is located on a shoulder position may be more susceptible to soil erosion.

4.1.2 Soil Color

Table 4.2 shows that the color of the soil solum ranged from a 5YR hue for Pedons 1 through 4 to a 7.5YR hue for Pedons 5 and 6 at

Table 4.1 Range of Soil Depth of Pedons 1 through 6.

Pedon No.	Elevation (m)	Ap horizon thickness (cm)	Solum thickness (cm)
1	37	26	26
2	189	26	60
3	366	29	>150
4	503	28	>150
5	640	29	63
6	732	31	>150

the higher elevations. In general, the soil was redder at the lower elevation.

According to Schwertmann et al. (1982), and Birkeland (1984), hematite is commonly associated with the 5YR hue and goethite with the 7.5YR and 10YR hues; the the degree of redness in soils normally being affected by climate.

According to Schwertmann et al. (1982), the yellowish-brown color in soils is due mainly the presence of goethite which is usually more abundant in wetter and cooler climates, while the red color is due to hematite which is more dominant in soils of the warmer areas. In cooler and/or wetter regions, it is also thought that the higher concentration of organic compounds complexes Fe and prevents the formation of hematite. In areas where temperatures are high and the soils are well aerated, however, organic matter is rapidly decomposed and Fe is released more readily. The red color in soils, therefore, is an indication of good drainage, good aeration, influence of parent material, and relatively more intense weathering over considerable time (Soil Survey Staff, 1975).

Although the soils of the lower elevations are slightly redder than those of the higher elevations, all six pedons are well-drained soils with good aeration. Furthermore, the Munsell color value is darker than 3.5 when moist and 5.5 when dry, and the chroma is less than 3.5 when moist. Pedons 1 through 6, therefore, meet the color requirements of the mollic epipedon.

4.1.3 Structure and Consistence

Table 4.2 also shows the structure and consistence of the soils. All of them had a moderate or strong structure in the surface horizons with a hard or very hard dry consistence, except for Pedon 4 which was both massive and very hard. With organic matter and the iron oxides present in these soils, waterstable aggregates are characteristic features. Aggregate stability is associated with good trafficability, good tilth, stable pores, and high water intake, and soils with such properties are well drained and have good air and water movement.

According to Soil Survey staff (1975), the soil structure of the mollic epipedon should be strong enough that major part of the horizon is not both massive and hard or very hard when dry. All of the pedons except Pedon 4 thus qualify as having a mollic epipedon.

Table 4.2 Morphological Properties of Pedons 1 through 6.

Hor.	Depth (cm)	Color Moist	Color Dry	Texture*	Structure**
		Pedon 1.	Elevation = 37 m		
Ap	0-26	5YR3/3	5YR4/4	vstsicl	2vfgr
Cr	26-52	10YR8/2	10YR8/2	-	-
R	52-80	-	-	-	-
		Pedon 2.	Elevation = 139 m		
Ap	0-5	5YR3/2	5YR4/3	vstsicl	2f&vfgr
AB	5-26	5YR3/2	-	stsicl	1f&msbk
BC	26-60	7.5YR3/2	-	sicl	1f&msbk
Cr	60-72				
		Pedon 3.	Elevation = 366 m		
Ap1	0-10	5YR3/2	5YR4/3	sicl	2vc&cpl
Ap2	10-29	5YR3/2	5YR4/3	sicl	1f&msbk
Bw1	29-48	5YR3/3	5YR4/4	sicl	1f&msbk
Bw2	48-82	5YR3/3	5YR4/4	sicl	2f&msbk
2Bw3	82-122	10YR3/2 7.5YR3/4	10YR4/3 7.5YR4/4	sicl	3vf&fsbk
2Bw4	122-155	10YR3/2	10YR5/2	sicl	2vf&fsbk
		Pedon 4.	Elevation = 503 m		
Ap	0-28	5YR3/2	5YR4/3	sic	m-1fgr
Bw1	28-63	5YR3/2	5YR4/3	sic	1cpr- 3vf&fsbk
Bw2	63-82	5YR3/2	5YR4/2	sic	1cpr- 3vf&fsbk
Bw3	82-130	5YR3/2	5YR4/3	sic	3vf&fsbk
Bw4	130-156	5YR3/2	5YR4/3	sic	2vf&fsbk
		Pedon 5.	Elevation = 640 m		
Ap1	0-7	7.5YR3/2	10YR4/3	sic	3vf&fgr
Ap2	7-29	7.5YR3/2	-	sic	1vfgr
Bw	29-63	5YR3/2	-	sic	2f&msbk
CB	63-97	5YR3/2	-	sic	2f&msbk
		Pedon 6.	Elevation = 732 m		
Ap	0-31	7.5YR3/2	7.5YR3/2	sicl	2vf&fgr
Bw1	31-46	7.5YR3/2	7.5YR3/2	sicl	1vf&fsbk
Bw2	46-58	7.5YR3/2	7.5YR3/2	sicl	1f&msbk
Bw3	58-88	7.5YR3/2	7.5YR3/2	grsicl	2vf&fsbk
B/C	88-160	7.5YR3/2	10YR4/2	grsicl	1vf&fsbk

*vst=very stony, st=stony, gr=gravelly, sicl=silty clay loam, sic=silty clay

**1=weak, 2=moderate, 3=strong, vf=very fine, f=fine, m=medium c=coarse, gr=granular, sbk=subangular blocky, pr=prismatic

Table 4.3 Morphological Properties (continued).

Hor.	Depth (cm)	Consistence Dry*	Moist**	Wet***	Roots\	Pores\	Boundary\\
				Pedon 1			
Ap	0–26	h	fr	ss,sp	3vf	3vf	c,w
Cr	26–60	–	–	–		3vf	
R	26–80						
				Pedon 2			
Ap	0–5	h	fr	s,p	3vf&1f	3vf	c,s
AB	5–26	h	fr	s,p	3vf&3f	2vf	g,s
BC	26–60	h	fr	s,p	2vf&2f	3vf&1f	g,i
Cr	60–72						
				Pedon 3			
Ap1	0–10	h	fr	ss,sp	3vf&2f	2vf	c,s
Ap2	10–29	h	fr	ss,sp	3vf&3f	3vf	g,w
Bw1	29–48	h	fr	ss,sp	3vf&2f	3vf	g,s
Bw2	48–82	h	fr	ss,sp	3vf	3vf	c,s
2Bw3	82–122	vh	fr	ss,sp	2vf	3vf	g,s
2Bw4	122–155	vh	fr	s,p	1vf	2vf	
				Pedon 4			
Ap	0–28	vh	fi	vs,vp	2vf&1f	3vf	a,s
Bw1	28–63	vh	fi	vs,vp	1vf	2vf	g,w
Bw2	63–82	vh	fr	vs,vp	1vf	2vf	g,w
Bw3	82–130	vh	fr	vs,vp	1vf	3vf	c,w
Bw4	130–156	vh	fr	vs,vp	1vf	2vf	
				Pedon 5			
Ap1	0–7	h	fi	vs,vp	2vf	3vf	g,s
Ap2	7–29	vh	vfi	vs,vp	1vf	3vf	c,s
Bw	29–63		fr	vs,vp	1vf	3vf	c,w
CB	63–97		fr	vs,sp	–	–	g,w
				Pedon 6			
Ap	0–31	h	fi	ss,sp	3vf	3vf	c,s
Bw1	31–46	h	fr	ss,sp	3vf&1f	2vf	g,s
Bw2	46–58	vh	fr	s,sp	3vf	3vf	g,w
2Bw3	58–88	vh	fr	s,p	3vf	3vf	g,w
2B/C	88–160	h	fr	ss,sp	2vf	3vf	

*h=hard, vh=very hard, **fi=firm, fr=friable,
***ss=slightly sticky, s=sticky, vs=very sticky, p=plastic
\1=few, 2=common, 3=many, f=fine, vf=very fine
\\a=abrupt, c=clear, g=gradual, s=smooth, w=wavy, i=irregular

Although Pedons 1 through 5 were consistently hard or very hard, they have a mollic epipedon because of adequate structural development. Normally, a hard consistence is not associated with a Mollisol, but that under conditions of intense weathering in the tropics, it is common that the iron oxides together with organic matter can form hard or very hard aggregates.

4.2 Physical Properties

The results of the particle size analysis as well as the calculation of clay content and values of soil water, bulk density, and coarse fraction content of the soils are discussed in this section.

4.2.1 Particle Size Distribution

In Table 4.3, the 15-bar to clay ratio is more than 0.6 for Pedons 2 and 3 and for some horizons of Pedons 1 and 6, and it indicates that the soils were poorly dispersed. The following relationship was, therefore, used to estimate the clay content:

Percent clay = 2.5 x 15-bar water content.

According to the Soil Survey Staff (1975), the above relationship provides a good estimate of the clay content as long as the soil does not have high amounts of organic matter and non-crystalline materials. Because both materials have high specific surface and hold high amounts of water at 15 bars, the use of such a relationship will overestimate the clay content.

Although the relationship was originally intended for soils with an oxic horizon, it provides a good estimate for the soils in this

Table 4.3 Comparison of The Measured and Estimated Clay Content of Pedons 1 through 6.

Horizon	Depth (cm)	15-bar/ clay	Clay*	Clay**
		Pedon 1		
Ap	0–26	0.53	34.4	45.3
Cr	26–52	0.74	21.1	39.0
		Pedon 2		
Ap	0–5	1.00	18.7	47.0
AB	5–26	0.84	21.4	45.0
BC	26–60	0.65	27.6	44.7
		Pedon 3		
Ap1	0–10	0.80	25.6	51.0
Ap2	10–29	0.95	21.7	51.5
Bw	29–48	0.88	24.2	53.3
Bw2	48–82	0.91	24.7	56.0
2Bw3	82–122	0.94	24.3	57.0
2Bw4	122–155	0.63	33.4	52.5
		Pedon 4		
Ap	0–28	0.32	66.7	53.3
Bw1	28–63	0.39	55.7	53.8
Bw2	63–82	0.38	58.2	54.9
Bw3	82–130	0.40	56.7	56.0
Bw4	130–156	0.43	45.2	57.8
		Pedon 5		
Ap1	0–7	0.44	50.6	55.5
Ap2	7–29	0.47	49.5	58.4
Bw	29–63	0.44	65.5	71.5
CB	63–97	0.51	52.2	66.5
C	97+	0.83	26.3	55.0
		Pedon 6		
Ap	0–31	0.98	26.0	64.0
Bw1	31–46	0.68	32.6	55.5
Bw2	46–58	0.53	41.6	54.8
Bw3	58–88	0.55	40.2	55.8
B/C	88–160	0.86	28.3	61.0

*Percent clay measured by the pipette method.
**Percent clay estimated by 2.5 x 15-water.

study because they have the same kind of water stable aggregates and similar physical and chemical properties.

The estimated clay content in Table 4.3 shows that there was about an even distribution of clay with depth. The clay content of the control section, however, showed an increase going from Pedons 1 to 6, although there was a slight decrease in Pedon 6 (Figure 4.1).

The lack of clay translocation in these soils is likely to be due to the low amounts of rainfall which normally moves the fine particles through the soil profile. The clay content, nevertheless, is appreciable because the weathering of basaltic parent rock is normally associated with high soil clay content. The increase in the clay content from Pedons 1 to 6 is associated with the increase in rainfall distribution. As mentioned earlier, increase in weathering and soil formation is associated with increase in soil moisture.

4.2.2 Bulk Density and Water Content

In Table 4.4, the bulk density ranges from 1.1 to 1.3 for Pedons 1, 3, and 4, with the values being slightly lower for Pedon 6. Values such as 1.1 to 1.3 are commonly associated with cultivated soils. Values such as the 0.95 for Pedon 6 could be associated with volcanic ash contribution because this pedon is located closer to mapping units of volcanic ash soils than any of the other pedons. Organic matter as well as volcanic ash increase the void volume of soils and thus reduce the bulk density.

In general, stone fragments in soils increase their bulk density (Lal, 1980). Although there were large amounts of rock fragments in

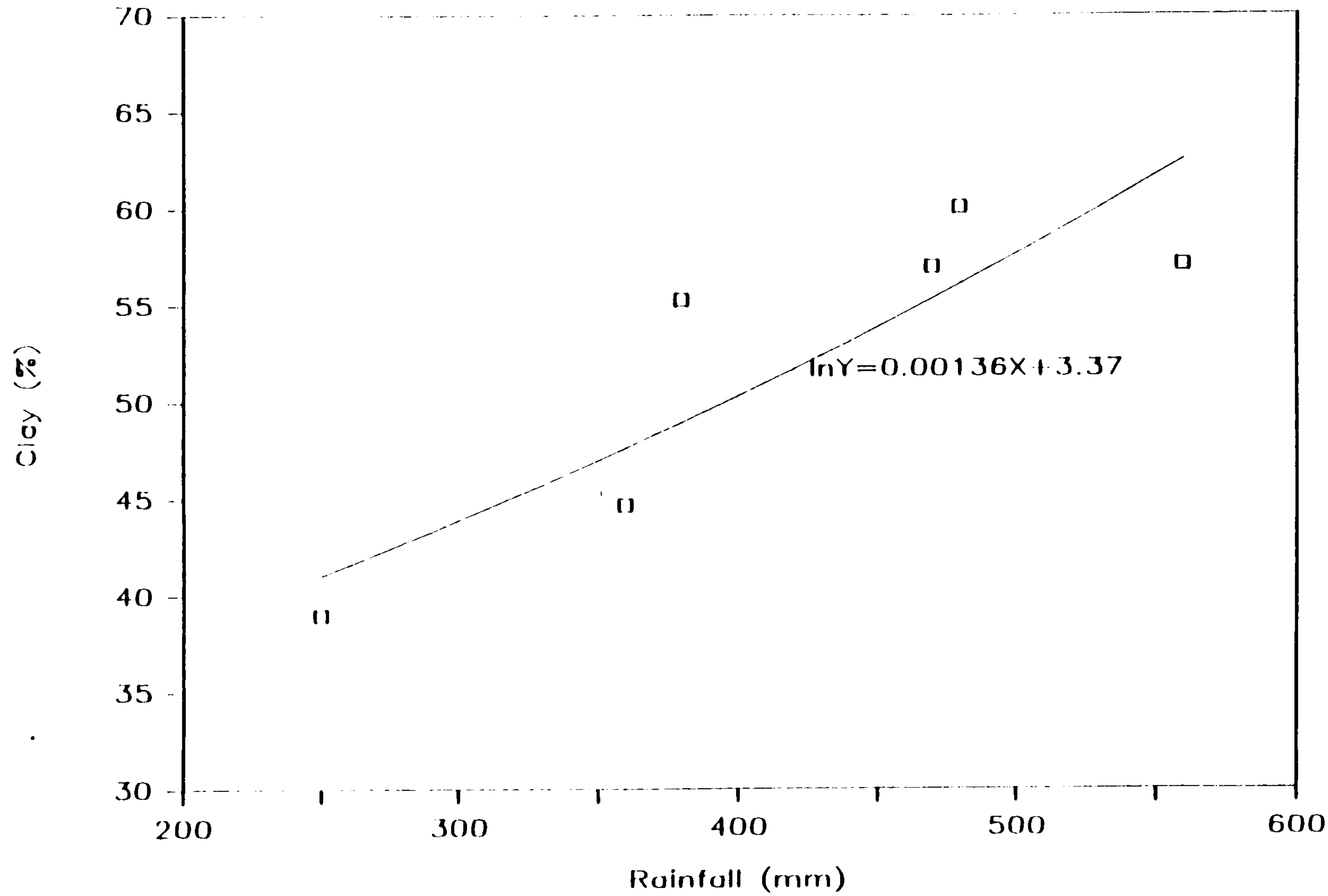

Figure 4.1 Relationship Between Clay Content of Control Section and Mean Annual Rainfall of Pedons 1 through 6.

the soils of the study area, the bulk density of Pedons 1, 3, and 4 did not show a great difference, because the samples for bulk density were collected from between the rock fragments.

Table 4.4 also shows the water content as determined at 1/3- and 15-bar retention. The available water holding capacity of the soils, the difference between 1/3 and 15-bar water content, varied from 3 percent in a subhorizon of Pedon 3 to about 53 percent in Pedon 6. The 15-bar water content increased from the lower elevations to the higher elevations and can be related to increasing rainfall distribution and increasing clay and organic matter content.

According to Lal (1980), the amount of water retained at any suction is influenced by the amount and nature of the clay and by organic matter. The high 1/3-bar water content in Pedon 6 may also be related to the high water holding capacity of volcanic ash materials.

4.2.3 Rock Fragments

In addition to the bedrock or lithic contact at shallow depth, rock fragments, or the materials greater than 2 mm in size, were common in the study area. Cobble- and stone-size coarse fragments (10 to 25 cm) were most apparent on the surface at the lowest elevation where Pedons 1 and 2 were studied. Although these surface materials decrease at the higher elevations, the amount of rock fragments increased in the solum at the higher elevations where Pedons 5 and 6 were located.

Table 4.4 Moisture properties of Pedons 1 through 6.

Hor.	Depth	CF	Bulk density 1/3	Bulk density O.D	Water content 1/3-bar	Water content 15-bar
	-cm-	%	---cm/cm---		---%---	
			Pedon 1			
Ap	0-26	50	1.20	1.29	28.3	18.1
Cr	26-52	32	-	-		15.6
			Pedon 2			
Ap	0-5	30	-	-	22.7	18.8
AB	5-26	36	-	-	21.0	18.0
BC	26-60	-	-	-	23.6	17.9
			Pedon 3			
Ap	0-10	-	1.29	1.38	29.3	20.4
Ap2	10-29	-	1.08	1.18	30.5	20.6
Bw1	29-48	8	1.12	1.24	29.7	21.3
Bw2	48-82	-	1.17	1.28	30.3	22.4
2Bw3	82-122	-	1.14	1.31	37.8	22.8
2Bw4	122-155	-	1.30	1.44	31.8	21.0
			Pedon 4			
Ap	0-28	1	1.33	1.48	26.9	21.3
Bw1	28-63	tr	1.29	1.42	27.1	21.5
Bw2	63-82	tr	1.34	1.46	27.4	21.9
Bw3	82-130	tr	1.44	1.56	26.7	22.4
Bw4	130-156	tr	1.39	1.51	28.6	23.1
			Pedon 5			
Ap1	0-7	10	-	-	-	22.2
Ap2	7-29	15	-	-	-	23.3
Bw	29-63	20	-	-	-	28.6
CB	63-97	35	-	-	-	26.6
C	97+	40	-	-	-	22.0
			Pedon 6			
Ap	0-31	11	0.95	1.09	42.5	25.6
Bw1	31-46	3	1.01	1.13	38.6	22.2
Bw2	46-58	9	1.08	1.28	38.2	22.9
Bw3	58-88	38	1.11	1.25	35.1	22.3
B/C	88-160	56	0.74	0.91	77.4	24.4

CF = coarse fraction, O.D. = oven dry, tr = traces.

The increase in the rock fragments with soil depth at the high elevation may be due to the exposure of saprolite as erosion removed the surface materials.

Pedons 3 and 4 had the least amount of rock fragments throughout the profile. A stone line, however, was observed in Pedon 3 at the 29-48 cm depth. Stone lines are normally associated with erosion and deposition, and their presence suggests that there may be more than one parent material with a discontinuity at the stone line. In Pedon 3, the stone line appears to separate two alluvial parent materials. Both are highly weathered and bear no resemblance to the original parent rock, showing very little rock strucure in the soil matrix.

The volume, size, and distribution of the rock fragments reflect the mode of soils formation and their relative ages. While recognizing the presence of the residual parent rock or the lithic contact, the different sizes of the fragments on the surfaces of Pedons 1 and 2 show that they were transported and deposited. At the same time, the assortment of sizes and quantities near the surface and with soil depth further indicate that soils such as Pedon 6 were formed from alluvial as well as residual parent materials. Based on the landscape position, it is probable that colluvial materials may also be associated with Pedon 6.

A summary of the different parent materials is presented in Table 4.5.

Table 4.5 Parent Materials of The Soils.

Pedon	Parent material	Remarks
1, 2	Alluvium over basalt residuum	Uneven distribution of rock fragments in solum directly underlain by bedrock.
3	Two seperate alluvial deposits	Soil material has a stone line, and color of the soil above and below the stone line is different.
4	Alluvium	Rock fragments observed in the surface only.
5	Basalt residuum	The proportion of rock fragments inreases with depth until the parent rock is reached.
6	Alluvium over residuum, both with volcanic ash influence	Uneven distribution of rock fragments near the surface, then a definite increase with soil depth; Low bulk densities.

4.3 Chemical Properties

The results of the chemical analyses are discussed in this section, and they include soil pH, base status, cation exchange capacity (CEC), and relationship of organic C to CEC.

4.3.1 Soil pH

Table 4.6 shows that the soil pH was neutral in Pedon 1 but became acidic in the other pedons with increasing elevation and rainfall. These results indicate that soil acidity increases with increase in leaching and organic matter content which are in turn associated with increase in rainfall and a decrease in temperature. The higher acidity in Pedons 2 and 5 over others can also be attributed to management; that is, the application of ammonium fertilizers and subsequent acidification in the sugar field and at the Pulehu Experimental Farm, respectively. Except for Pedon 2, the pH of the surface soils of the study area was above 5.5, indicating the absence of KCl extractable Al or the associated Al toxicity.

In all of the pedons, except 6, the surface soil was slightly more acidic than the subsoil, and the trend may be associated with the organic matter content and/or management. The soil pH in KCl solution was also lower than the soil pH in water, and this indicates that the soil colloids had a net negative charge. The difference in these two pH values, or the delta pH, however, is small and further indicates that the soils are dominated by minerals with variable charge.

Table 4.6 The soil pH of Pedons 1 through 6.

Horizon	Depth (cm)	pH water	pH KCl	pH NaF	delta pH $pH_{KCl}-pH_{water}$
			Pedon 1		
Ap	0–26	7.1	7.2	9.5	+0.1
CR	26–52	7.9	7.3	9.8	-0.6
			Pedon 2		
Ap	0–5	5.2	4.8	9.6	-0.4
AB	5–26	5.4	5.1	9.5	-0.3
BC	26–60	5.6	5.2	9.8	-0.3
			Pedon 3		
Ap1	0–10	7.0	6.3	-	-0.7
Ap2	10–29	7.1	6.4	9.2	-0.7
Bw1	29–48	7.2	6.4	-	-0.8
Bw2	48–82	7.3	6.7	9.9	-0.8
2Bw3	82–122	7.3	6.7	10.3	-0.6
2Bw4	122–155	7.4	6.6	-	-0.8
			Pedon 4		
Ap	0–28	6.1	5.9	9.0	-0.2
Bw1	28–63	6.3	5.9	-	-0.4
Bw2	63–82	6.5	6.3	9.5	-0.2
Bw3	82–130	6.8	6.7	-	-0.1
Bw4	130–156	6.8	6.7	9.5	-0.1
			Pedon 5		
Ap1	0–7	5.6	5.2	9.3	-0.4
Ap2	7–28	5.7	5.2	9.2	-0.5
Bw	29–63	5.7	5.3	9.2	-0.4
CB	63–97	5.8	5.3	9.2	-0.5
C	97+	5.9	5.4	9.4	-0.5
			Pedon 6		
Ap	0–31	6.1	5.3	9.3	-0.8
Bw1	31–46	6.6	5.9	9.7	-0.7
Bw2	46–58	6.1	5.4	9.4	-0.7
Bw3	58–88	5.6	4.8	-	-0.8
B/C	88–160	5.8	4.7	9.6	-0.9

4.3.2 Extractable Bases, Base Saturation, and Organic Carbon

Table 4.7 shows not only the base status and organic C but also the effective cation exchange capacity (ECEC). The sum of extractable bases is expressed as ECEC because of the absence of KCl-extractable Al. The data show that the soils had high amounts of extractable Ca, Mg, and K and that all of the pedons had base saturation of more than 50 percent, except Pedon 6 which had base saturation less than 50 percent in the horizon near the paralithic contact.

These results including the ECEC, thus, indicate that these soils are productive agricultural soils. Extractable ions in such soils are almost always Ca > Mg > K (Bohn *et al.*, 1979). Because of the high base saturation (over 50 percent), these soils, except Pedon 6, are further classified as Mollisols. Pedon 6 missed being classified as a Mollisol because the base saturation in the subsoil was slightly less than 50 percent.

4.3.3 Organic Carbon and Cation Exchange Capacity

In Table 4.7, the organic C increased from about 1 percent in Pedon 1 to about 4 percent in Pedon 6, with the values decreasing with soil depth at each site. Figure 4.2 shows that the organic C of the surface 25 cm, taken as weighted average values, increased with the decreasing temperature from Pedon 1 to Pedon 6. Conversely, there is minimal organic matter accumulation in the lower elevations which are chracterized by low rainfall and high temperature which in turn result in the rapid decomposition of organic residues.

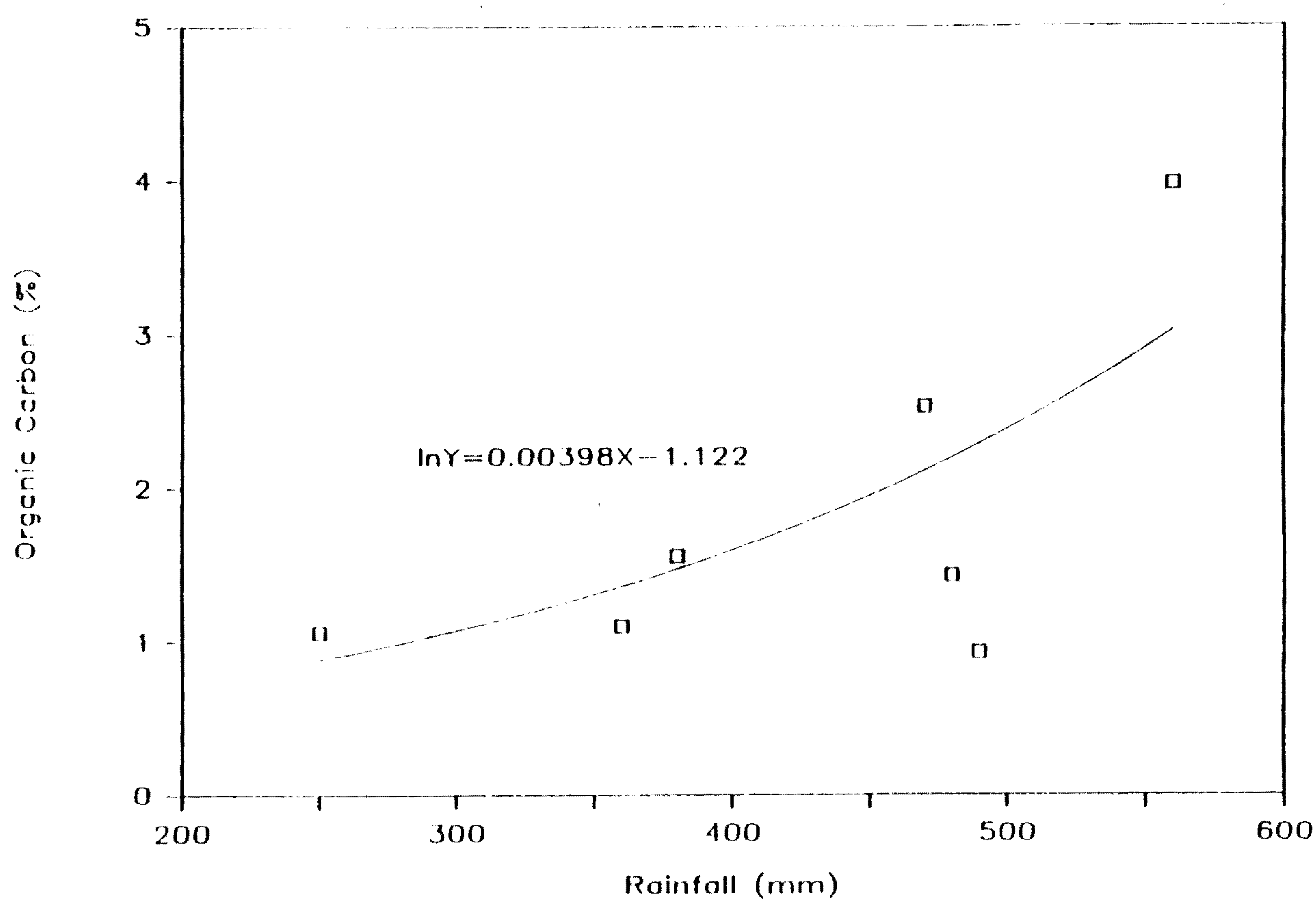

Figure 4.2 Relationship between Organic Carbon and Mean Annual Rainfall.

Table 4.7 Chemical Properties of Pedons 1 through 6.

Depth	Extractable bases				ECEC	NH_4OAc Base sat.	OC
	Ca	Mg	Na	K			
cm	meq / 100g					percent	
			Pedon 1				
0–26	7.2	4.2	0.5	1.9	13.8	88	1.06
26–60	8.4	3.7	2.2	1.8	16.1	92	0.90
			Pedon 2				
0–5	14.5	3.0	0.3	4.5	22.3	100	2.66
5–26	6.6	1.9	0.2	3.5	12.1	81	0.72
26–60	5.1	1.5	0.2	4.1	10.8	78	0.84
60–72	7.2	2.1	0.6	4.1	14.0	77	1.03
			Pedon 3				
0–10	15.6	5.9	tr	3.4	24.9	94	1.96
10–29	14.3	5.5	0.5	2.7	23.0	94	1.29
29–48	11.5	4.7	tr	1.3	17.5	87	1.46
48–82	10.4	4.3	0.5	2.7	23.0	92	0.78
82–122	9.0	2.7	1.4	0.1	13.2	84	0.53
122–155	6.3	2.0	1.5	tr	9.8	73	0.42
			Pedon 4				
0–28	12.2	2.3	0.2	4.6	19.3	89	1.46
28–63	11.0	2.8	tr	3.7	17.5	95	1.19
63–82	9.5	3.1	0.1	2.4	15.1	100	0.66
82–130	12.3	3.8	0.3	0.5	16.9	100	0.46
130–156	13.4	3.7	0.4	0.2	17.7	100	0.34
			Pedon 5				
0–7	15.7	3.7	0.3	4.1	23.8	68	2.49
7–29	17.7	4.1	0.3	3.5	13.8	71	2.54
29–63	15.0	3.6	1.1	0.7	6.8	65	0.83
63–97	16.0	3.6	1.1	0.7	4.1	75	0.77
97+	14.8	2.9	1.2	0.1	2.3	78	0.43
			Pedon 6				
0–31	15.5	5.4	0.9	1.2	23.0	59	3.98
31–46	11.4	5.2	0.9	0.3	17.6	72	2.05
46–58	4.6	3.5	0.8	0.1	9.0	58	1.01
58–88	2.6	2.7	1.0	0.1	6.4	46	0.87
88–160	1.1	2.6	1.5	0.1	5.3	29	0.92

Table 4.8 The CEC Values of Pedons 1 through 6.

Horizon	Depth (cm)	CEC*	CEC**	CEC***
		Pedon 1		
Ap	0–26	15.6	45.3	34.4
CR	26–52	17.5	82.9	44.8
		Pedon 2		
Ap	0–5	22.4	99.3	47.6
AB	5–26	15.0	70.0	33.3
BC	26–60	13.9	50.4	30.1
		Pedon 3		
Ap1	0–10	26.4	103.1	51.8
Ap2	10–29	24.5	112.9	47.6
Bw1	29–48	20.0	82.6	37.5
Bw2	48–82	16.9	68.4	30.2
2Bw3	82–122	15.7	64.6	27.5
2Bw4	122–155	13.4	40.1	25.5
		Pedon 4		
Ap	0–28	21.7	32.5	40.7
Bw1	28–63	18.5	33.2	34.4
Bw2	63–82	15.0	25.8	27.3
Bw3	82–130	14.5	25.6	25.9
Bw4	130–156	15.2	33.6	26.3
		Pedon 5		
Ap1	0–7	35.3	69.8	63.6
Ap2	7–29	36.0	72.7	61.7
Bw	29–63	31.3	47.8	43.8
CB	63–97	28.2	54.0	42.4
C	97+	24.5	81.7	44.5
		Pedon 6		
Ap	0–31	38.9	149.6	60.8
Bw1	31–46	24.5	75.1	44.1
Bw2	46–58	15.5	37.2	28.3
Bw3	58–88	13.9	34.6	24.9
B/C	88–160	18.2	64.3	29.8

*Meq per 100 g soil.
**Meq per 100 g of measured clay.
***Meq per 100 g of clay estimated by 2.5 x 15-bar water.

Organic C content also correlates with clay content. Anderson and Paul (1984) have shown that organo-mineral complexes stabilize and protect organic matter from rapid decomposition.

Figures 4.3 shows the relationship between organic carbon and CEC. Table 4.8 further shows that when the effect of organic C is removed, the CEC of the inorganic soil materials ranged from 16 to 36 meq/100 g of clay. Because the mineralogical analysis showed kaolinite to be the dominant clay mineral, it was expected that the CEC values would be much lower. It is probable that other constituents such as weatherable minerals and amorphous clay materials may be present, and further mineralogical studies are in order.

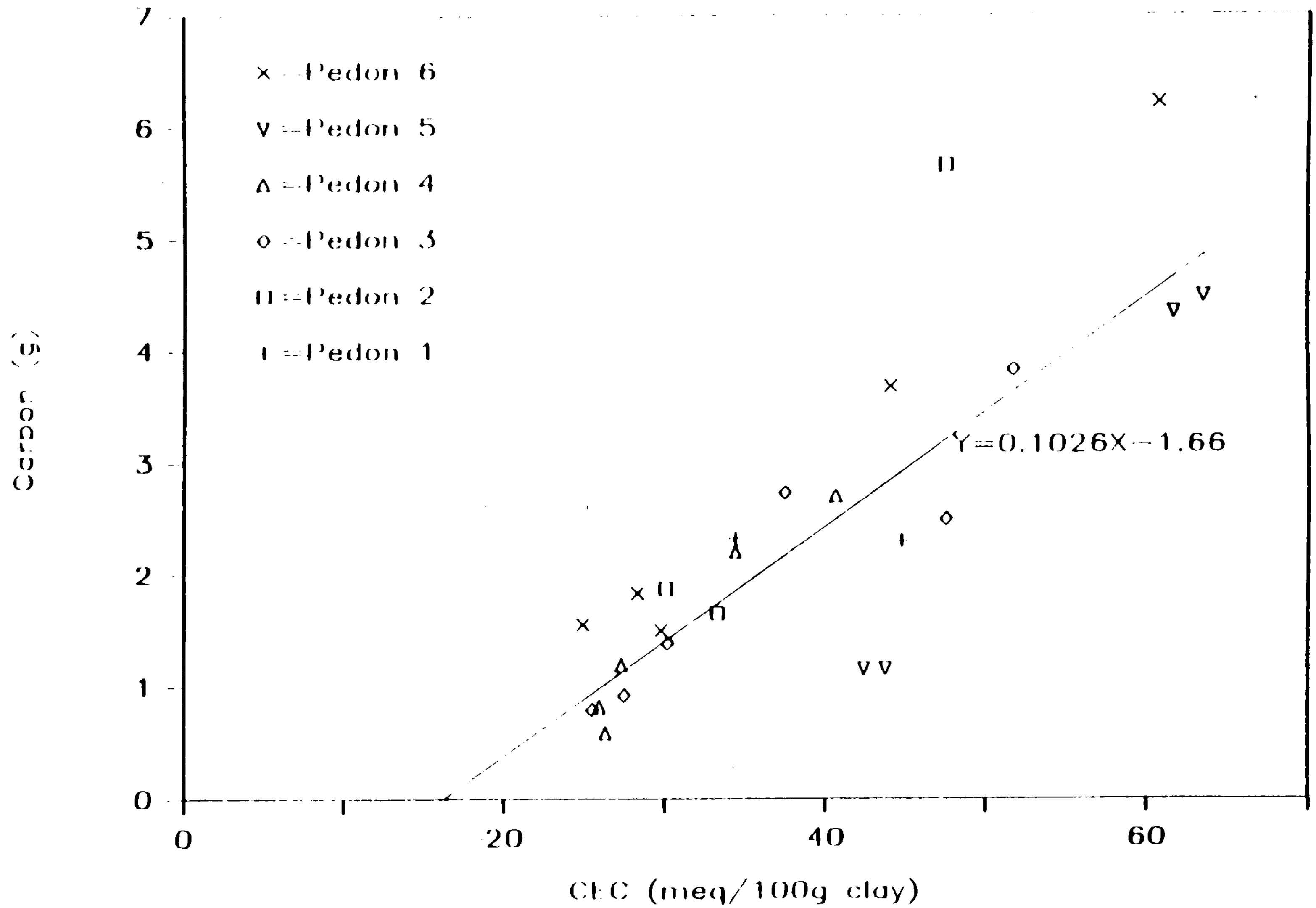

Figure 4.3 Relationship between Organic Carbon and CEC of Pedons 1 through 6.

Table 4.9 CEC of The Inorganic Soil Material.

Pedon No.	Organic free clay CEC meq/100 g
2	24.0
3	16.7
4	20.0
5	36.1
6	15.6

V. SOIL CLASSIFICATION

According to the Soil Survey Investigation Report No. 29 (SCS, USDA, 1976), the Waiakoa and Keahua soil series are classified as members of the fine, kaolinitic, isohyperthermic family of Torroxic Haplustolls. This study however, showed that Pedon 1 is classified as Lithic Haplustolls, while Pedons 2, 3, and 5 are classified as Cumulic Haplustolls. Pedons 4 and 6 are not Mollisols and are classified as Inceptisols (Tropepts).

Pedon 1 is classified as Lithic Haplustolls because it has a lithic contact within 50 cm of the surface. Pedons 2, 3, and 5 are Cumulic Haplustolls because they have more than 0.3 percent organic carbon throughout the depth of the soil profile and because they have a mollic epipedon that is more than 50 cm thick and a texture that is finer than loamy fine sand.

Pedons 4 and 6 are not Mollisols because they do not have a mollic epipedon. In Pedon 4, the structural requirement was not met, and in Pedon 6, the base saturation was less than 50 percent below a depth of 58 cm. Based on the data, Pedon 4 is thus classified as Fluventic Ustropepts, while Pedon 6 is classified as Ustic Humitropepts.

The requirements of Torroxic Haplustolls are presented in Table 5.1, while the reasons for the new taxonomic names for Pedons 1 through 6 are outlined in Tables 5.2.

Based on this study, the Waiakoa and Keahua soils are classified as other than Torroxic Haplustolls. However, because the pedons were

Table 5.1 Present Classification of The Soils in The Study Area.

Present Classification	Requirements
Torroxic	Have less than 24 meq CEC per 100g clay (by NH_4OAc) below a depth of 25 cm but above a 1-m depth; are moist in the moisture control section for 90 consecutive days or more.
Haplustolls	Have a mollic epipedon; have an aridic or an ustic moisture regime that borders on aridic.
clayey	Have more than 35 percent clay in the fine earth fraction.
kaolinitic	Have more than half kaolinite and less than 10 percent montmorillonite.
isohyperthermic	Mean annual soil temperature is $22^{o}C$ or higher.

Table 5.2 Proposed Classification of The Sampled Pedons in The Study Area.

Pedon	Proposed classification	Remarks
1	Lithic	Has a lithic contact within 50 cm of the surface.
	Haplustolls	(as in Table 5.1).
	clayey-skeletal	Has a clayey particle size class in the fine earth fraction but also has rock fragments that make up more than 35 percent by volume.
	kaolinitic	(as in Table 5.1).
	isohyperthermic	(as in Table 5.1).
2	Cumulic	Has more than 0.3 percent organic carbon throughout the depth of the soil profile; Has a mollic epipedon that is more than 50 cm thick and a texture that is finer than loamy fine sand.
	Haplustolls	(as in Table 5.1).
	clayey-skeletal	(as for Pedon 1).
	kaolinitic	(as in Table 5.1).
	isohyperthermic	(as in Table 5.1).
3	Cumulic	(as for Pedon 2).
	Haplustolls	(as in Table 5.1).
	clayey	(as in Table 5.1).
	kaolinitic	(as in Table 5.1).
	isohyperthermic	(as in Table 5.1).

Table 5.2 (cont.)

Pedon	Proposed classification	Remarks
4	Fluventic	Has > 0.2 percent organic C at the depth of 1.25 m.
	Ustropepts	Is both massive and very hard in the surface and did not qualify as a Mollisol; Has an ustic moisture regime and a base saturation by NH_4OAc > 50 percent in all subhorizons between depths of 25 cm and 100 cm.
	fine	Has more than 35 but less than 59 percent clay in the fine earth fraction.
	kaolinitic	(as in Table 5.1).
	isohyperthermic	(as in Table 5.1).
5	Cumulic	(as for Pedon 2).
	Haplustolls	(as in Table 5.1).
	clayey	(as in Table 5.1).
	kaolinitic	(as in Table 5.1).
	isohyperthermic	(as in Table 5.1).

Table 5.2 (cont.)

Pedon	Proposed classification	Remarks
6	Ustic	Has an ustic moisture regime;
	Humitropepts	Has an iso- temperature regime warmer than isomesic; has base saturation <50 percent by NH_4OAc in some horizons between 25 and 100 cm depths, and has more than 12 kg organic carbon per m^2 to a depth of 1 m.
	fine	(as for Pedon 4).
	kaolinitic	(as in Table 5.1).
	isothermic	Soil temperature is $15^{\circ}C$ or higher, but lower than $22^{\circ}C$.

sampled at a given location, the classification name obtained in this study should not necessarily replace the original classification.

It is recognized that a soil mapping unit of a high intensity soil survey can allow up to 15 percent inclusions (Soil Survey Staff, 1951). Because the study area was mapped at a high to medium intensity (Foote et al., 1972), it is likely that this area may have more than 15 percent inclusions of other soils.

Actually, the reclassification of Torroxic to Cumulic or Lithic subgroups may not be so critical if the soils are devoted to present day land use. The reclassification may be important, however, if alternative uses are to be made of this study area.

This study further shows that although Pedons 3, 4, and 5 (all Keahua) were isohyperthermic soils, Pedon 6 (also Keahua) was an isothermic soil. Differentiation of the soil temperature regime may be important for production of certain vegetables and flowers such as head cabbage and proteas, respectively.

Because of the limited sampling, there is a need to examine the dominant soils of the sampling area. There is also a need to delineate the isothermic soil from the isohyperthermic soil.

VI. LAND USE POTENTIAL

The soils in the study area are well drained, have good tilth, are adequately deep for most crops in at least half of the area (Keahua soil), and are quite fertile. The most limiting factor for plant growth is moisture availability. The low rainfall has led to underutilization, and there is a need to seek alternative uses for better land utilization. In this study, economic consideration is recognized but not included in the evaluation.

As mentioned earlier, areas of the shallow Waiakoa soil are mostly in pasture or grassland with xerophytic vegetation. Some of these lands, especially near the ocean or at low elevation, are also in urbanization or non-agricultural use. It is anticipated that much more of these lands may be rezoned to urban uses such as for an industrial park.

It is probable that the present land use of pasture may be the best use. On occasions, however, there are proposals for alternative uses; for example, for a 400-hectare jojoba plantation. A vegetable farmer also farms the Waiakoa soil at the low elevation. Perhaps, there may be opportunities to re-expand the area to vegetables, especially for crops such as tomatoes. In many semi-arid areas of the tropics, cassava is produced for animal feed. Perhaps, this root crop may be a potential feed crop for animals in addition to the buffel grass now in existence in the area.

The purpose of this chapter is to assess the landuse potential of the Mollisols of this area (Waiakoa and Keahua soils) for three crops: Cassava, jojoba, and tomatoes. Such an evaluation can provide a potential land user with some information on the suitability of these crops. The following sections summarize the requirements of these crops, and these requirements are used to match the soil and land characteristics (land qualities) of the area in suggesting the suitability of the soils for the specified use.

6.1 Crop Requirements of Cassava

Cassava, a lowland tropical root crop, is an important food and carbohydrate source in many parts of the lowland tropics. Although essentially a New World food crop, cassava is also used as feed for livestock.

6.1.1 Growth Requirements

Rainfall—Cassava grows best in the humid tropics and subtropics where rainfall ranges from 1000 to 1500 mm, but it does well in areas with annual rainfall as low as 500 mm (Purseglove, 1974). Except at planting, it can withstand prolonged periods of drought. When moisture is low in the soil, cassava plants cease to grow and shed some of their leaves, thereby reducing their total transpiring surface. Growth, however, resumes quickly with the advent of rain. It can, therefore, be adaptable to certain regions with low and uncertain rainfall.

Temperature—Cassava cannot stand cold or frost at any time during its active growth period. Growth is most satisfactory at temperatures around 29°C and yields are drastically reduced below 16°C (Purseglove, 1974).

Soils—Cassava grows best on well drained sandy or sandy loam soils, but it can be grown on almost all soil types provided they are not waterlogged, too shallow or too stony. On clayey or poorly drained soils, root growth is poor, so that the tuber to root ratio is considerably reduced. Poor soil aeration also causes tuber to rot and gravelly and stony soils tend to hinder root penetration.

Daylength—Cassava production is reduced when daylength exceeds 10 to 12 hours.

6.1.2 Management requirements

Fertilization—Cassava can tolerate low levels of Ca, N, and K in the root environment and utilizes K efficiently in dry matter production. It is tolerant to pH as low as 3.5 and is resistant to high levels of Al and Mn but it is not tolerant to high salinity conditions. However, cassava can be exhaustive of potash, and, therefore, this nutrient requires some monitoring.

Pest/weed control—Weeds should be controlled during the early stages of growth. Diseases can best be controlled by planting disease-free cuttings and disease tolerant cultivars, and by isolation.

Harvesting and storage—Mature roots can be stored unharvested in the ground for several months. Once harvested, fungicidal wax coating has been found to extend storage life up to 2 weeks. Chipping and drying practices are used for longer-term storage to a year or more.

6.2 Crop Requirements of Jojoba

Jojoba is a perennial desert shrub that has become economically important because it produces oil of high purity. Its commercial importance arose from the fact that the oil it produces could in time replace the oil which is presently obtained from the endangered sperm whale.

6.2.1 Growth requirements

Temperature—Jojoba can tolerate temperatures as high as 65°C. Temperatures above 38°C, however, may reduce productivity because they cause the stomata to close, thereby reducing vegetative growth. The best temperature for germination is around 25°C. Flower buds and new seeds can be damaged at -2°C and killed at -6°C (National Research Council, 1985).

Moisture—Jojoba is drought tolerant and can survive arid environments. According to the National Research Council (1977), most natural stands grow in areas receiving 200–460 mm of annual precipitation. For quick plantation establishment, however, jojoba requires moderate amounts of water. For best yields and and maximum production, some irrigation may be necessary, especially when new flowers appear (Yermanos, 1979). The most critical period for moisture availability is during flowering and fruit development. Optimum annual precipitation is between 300 and 450 mm, but for economic reasons, 460–610 mm of annual rainfall is most suitable (National Research Council, 1985). Good drainage is vital because jojoba cannot survive waterlogging.

Soils—Jojoba grows well on sloping, well-drained coarse textured soils and on soils of loamy texture (Natural Vegetation Committee, 1973). Heavy clays may be suitable if they have good internal drainage as the plants cannot withstand waterlogging, and need good aeration. According to Thomson, (1982), jojoba should not be grown on heavy bottomland soils that are prone to flooding. Jojoba plants have roots that can go as deep as 13 m into the ground in search of moisture, but the feeding roots are found in the top 80 cm of the soil. Soil depth should therefore be at least 100 cm, and the underlying material easily penetrated by roots (National Research Council, 1985).

6.2.2 Management Requirements

Soil pH—Jojoba plants have been found to do very well in soils ranging from pH 5 to 8, but pH limits at which production would be adversely affected have not been determined (National Research Council, 1985).

Salinity—Being a desert plant, jojoba can tolerate low quality water provided drainage is adequate. Some varieties cannot tolerate salt stress well, and the result is damaged leaves, retarded growth and reduced flower production. High Na absorption ratios should be avoided (National Research Council, 1985).

Fertilization—The optimum fertilizer requirements of jojoba are not known at present. The plants have been found to respond positively to N and Zn, especially on sandy soils (National Research Council, 1985).

Pests and Diseases—On poorly drained soils, jojoba contracts waterborne fungal diseases. Fungal root diseases can also be a problem in nurseries. Several insect pests have been identified on jojoba plants, but there are only a few cases of any known economic damage (Thomson, 1982). Burrowing rodents often eat the roots but the problem can be reduced by setting traps (National Research Council, 1985).

6.2.3 Previous Work in Hawaii

Jojoba has been tried out in Hawaii previously, with successful planting on Maui at an elevation of 600 m. The major problem was the continuous flowering all year round because of the warm tropical climate. This is undesirable for machine-harvested crops, and chemical spraying has been suggested to control flowering (National Research Council, 1985).

6.3 Crop Requirements of Tomatoes

Tomatoes are generally warm season plants and are reasonably resistant to heat and drought. They, however, grow under a wide range of climatic and soil conditions in many regions of the world.

6.3.1 Growth Requirements

Temperature—The tomato thrives best when temperatures are uniformly moderate, between 18 and 29°C. Plants are usually frozen at temperatures below 0°C and plant growth is nearly stopped at temperatures below $10^{\circ}C$. Fruits do not increase in size at temperatures above $35^{\circ}C$. High temperatures accompanied by high humidity favor the development of foliage diseases. Fruit set in tomatoes is limited to a narrow range of night temperatures. According to George (1984), for most lines, fruit fails to set at $13^{\circ}C$ or below and is greatly reduced above $21^{\circ}C$. The most favorable night temperatures for fruit set lie between $15^{\circ}C$ and $21^{\circ}C$. High night temperatures result in bud drop and reduction of the quantity and functionality of the gametes. Hot drying winds cause flowers to drop (Gould, 1983).

Soils—Tomatoes can be grown in practically all kinds of soils, from sands to heavy clays (Work, 1926). Ideally, the best soils are deep loams that are well supplied with humus. Where an early crop is desired, the best soils are sandy loams, and where large yields are important, loams, clay loams and silt loams are preferred. Because tomatoes require good soil aeration, soils with possible water logging problems should be avoided. Tomato plants produce an extensive root system, and if rooting depth is unrestricted, their roots can grow as deep as 5 m (Mittleider, 1981). Deep soils, therefore, are the most suitable.

Moisture—Tomato plants require a continuous supply of water, but the medium of growth should also be well supplied with air. Soil moisture should be maintained near field capacity through most of the growing period (Mittleider, 1981). Tomatoes should be watered adequately everyday through their growing and producing season.

Day Length—Tomatoes are not sensitive to day length. They will set fruit in daylengths varying from 7 to 19 hours. Tomato requires 3 to 4 months from the time of seeding to produce the first ripe fruit. Shady places should be avoided for growing tomatoes because shading results in pro-duction of small and thin stems, and such plants are very low yielding.

6.3.2 Management Requirements

Fertilization—Tomato plants should be well supplied with N, P, K, Mg, Ca, Fe, S, Fe and Mo. Deficiencies of these elements may result in reduced yields. Soils should also be adequately supplied with organic matter. Nitrogen greatly influences the quality of the crop. There must be adequate N to produce enough foliage to protect the fruit from exposure to the sun. However, if there is too much readily available N, the crop is likely to become too vegetative and be late in maturing and producing fruit (Gould, 1983).

Soil pH—The soil should be only slightly acidic, and should be limed, if necessary, to raise the pH to the range of 6.0 to 6.5. Thisrange has been determined to be optimal for tomato production (Gould, 1983). If soil pH is 5.0 or less, application of 1 to 2 tons or finely ground lime is beneficial to the plants. If the soil is too alkaline for tomatoes, the area should either be avoided or the soil leached thoroughly before cropping.

Diseases and Pests—Pathogens associated with tomato plants are composed of bacteria, fungi, viruses, and nematodes (AVRD, 1979). These diseases and pests are most destructive in the tropics with warm wet weather. Severity also increases with decreasing soil drainage. Fungal infection can occur at temperatures ranging from 21-26^{o}C, with relative humidity above 95 percent (AVRD, 1982). Tomato varieties selected for the tropics should be heat and bacterial wilt tolerant (AVRD, 1985). To reduce the incidence of soil borne diseases, tomato crops should not be planted consecutively. In fact, a second crop should not be planted for at least six months after the harvest of a previous tomato crop (AVRD, 1985).

6.4 Soil Suitability Ratings for Selected Crops

According to the FAO land evaluation method (FAO, 1976), the land use description of the proposed crops may be listed as follows: (1) rainfed cassava production (low input); (2) rainfed jojoba production (intermediate input); (3) irrigated tomatoes (high input).

A low input for cassava means that the material inputs would consist mainly of the stalk cuttings, and that the fertilizer would only be applied to young seedlings to get them established. An intermediate input for jojoba means that some material inputs such as fertilizer, supplemental irrigation, chemical weed and pest control may be applied during the crucial periods in the growth of the plants or as needed to adequately increase yields. High input for tomatoes means that fertilizer and chemical weed and pest control would have to be applied to maximize yields or economic returns, and the crops have to be drip-irrigated, with all aspects of growth have to be closely monitored.

Table 6.1 shows the major limitations of the six pedons for crop production. In general, the moisture from rainfall was too low during the growing season and the soil depth was too shallow in Pedons 1 and 2 for the three crops. In addition, the available water capacity of Pedons 1 and 2 was inadequate for cassava production under rainfed condition.

For rainfed cassava with low input, moisture from rainfall was also a limitation for Pedons 3, 4, and 5. The available water capacity, in addition, was limiting in Pedons 4 and 5. Although moisture and available water capacity were not limiting in Pedon 6, the slightly cooler isothermic temperature appears to be a limitation.

For rainfed jojoba with intermediate input, temperature was the limiting factor for all of the pedons. According to the crop requirements, an experimental planting at the 600-m elevation (near Pedon 5) gave continuous flowering throughout the year because of the warm tropical climate. Such a statement implies that an isohyperthermic or an iso-temperature is a limitation for jojoba because of the induced continual flowering. In any case, if this elevation is too uniformly warm, the lower elevations (Pedons 1 through 4 would certainly be more uniformly warm and also be a limitation for jojoba. On the other hand, Pedon 6 not only has a

Table 6.1. Major Limitations for Cassava, Jojoba, and Tomatoes in the Study Area.

Pedon	Rainfed Cassava (low input)	Rainfed jojoba (inter. input)	Irrigated tomatoes (high input)
1	m, aw, d	m, d, t	m, d
2	m, aw, d	d, t	m, d
3	m	t	m
4	m, aw	t	m
5	m, aw	t	m
6	t	t	m, t

aw = available water capacity; d = soil depth;
m = moisture from rainfall; t = temperature.

uniform tropical climate but also has a cooler isothermic temperature which can be a limitation for jojoba.

The crop requirements show that there cannot be tomato production in Pedons 1 through 6 without irrigation throughout the year. Even with irrigation, soil depth still appears to be of some limitation in Pedons 1 and 2. This particular limitation is, however, absent in Pedons 3, 4, and 5 and is replaced by the limitation due to cooler temperature in Pedon 6.

These limitations associated with the crops suggest, as shown in Table 6.2, that Pedons 1 through 6 are not suited for cassava and jojoba under the conditions of the study. On the other hand, with irrigation and other forms of input, Pedons 1 and 2 are moderately suited, Pedons 3, 4, and 5 are highly suited, and Pedon 6 is moderately suited for tomato production. In making these statements, differences in crop performance due to cultivar were not considered.

Table 6.2 General Suitability Ratings for Cassava, Jojoba, and Tomatoes.

Pedon	Rainfed Cassava	Rainfed Jojoba	Irrigated Tomatoes
1	N	N	S2
2	N	N	S2
3	N	N	S1
4	N	N	S1
5	N	N	S1
6	N	N	S2

S1 = highly suitable; S2 = moderately suitable;
S3 = marginally suitable; N = not suitable

VII. SUMMARY AND CONCLUSION

Substantial areas of Mollisols occupy the isthmus and the lower western slopes of the Haleakala Mountain of Maui, Hawaii. The objectives of this study were to (1) assess the influence of soil forming factors associated with some of these Mollisols, (2) to characterize and classify the Mollisols in the study area, and (3) to assess the landuse potential of the soils for specified desired uses.

Pedons of six soils selected from the mapping units of the Waiakoa and Keahua soil series were sampled, characterized, and classified according to their morphological, physical, and chemical properties. The location of these soils ranged from 37-m elevation with less than 250 mm of rainfall (Waiakoa soil) to 732-m elevation with approximately 500 mm of rainfall (Keahua soil). The parent materials were primarily alluvial or residual material of andesitic composition over basalt. Of the soil forming factors, climate showed the dominant influence. Parent material as affected by erosion and deposition, and the addition of volcanic ash at one of the sites, also showed some effect.

The study of the six soils showed that with increasing rainfall, there was an increase in the clay content of the control section from about 38 to 60 percent. Soil acidity also increased, from about pH 7 to slightly less than 5.5, although this acidity was also affected by land use and soil management. Finally, organic carbon increased from about 1 to 4 percent. With the increase in rainfall, there was also a decrease in temperature going from the low elevation to the higher elevation. Although the increasing rainfall and cool temperature favor the accumulation of organic carbon, the maximum mean annual rainfall of only about 500 mm and the cool temperature did not contribute much else to soil formation. The soils, therefore, are all characterized by a high base status or high fertility and in general a moderate soil acidity for crop production.

These soils, however, differ to an extent in soil depth and the presence of rock fragments. In fact, the Waiakoa and Keahua soil mapping units are differentiated on these features, taking soil color also into consideration. Although there was an increase in the soil depth with increasing rainfall, there was also an increase in rock fragments in the soil solum (A and B horizons). The presence of these rock fragments can be associated with the kinds of parent material, whether alluvial or residual, as influenced by erosion and deposition. It is believed that the soils in the low rainfall area were shallow to bedrock and associated with many surface rock fragments because of the lack of soil development and the subsequent deposition of erosion material. On the other hand, there were more rock fragments in the soil solum in the higher rainfall area because of the surface erosion and the subsequent exposure of the saprolite.

The laboratory studies showed that the Waiakoa and Keahua soil series, which are classified as members of the fine, kaolinitic, isohyperthermic family of Torroxic Haplustolls, must be reclassified for the following reasons: Pedon 1 (Waiakoa) is a Lithic Haplustolls because of a lithic contact within 50 cm of the soil surface. Pedons

2 (Waiakoa), 3, and 5 (both Keahua) are Cumulic Haplustolls because they have more than 0.3 percent organic carbon throughout the depth of the soil profile and because they have a mollic epipedon that is more than 50 cm thick and a texture that is finer than loamy fine sand. Pedon 4 (Keahua) is not a Mollisols because it does not have a mollic epipedon, while Pedon 6 (also Keahua) is not a Mollisol because it does not have base saturation by ammonium acetate of 50 percent or more throughout the depth of the soil. Pedon 4 is classified as Fluventic Ustropepts and Pedon 6 as Ustic Humitropepts. Although the soil family remains the same for most of the soils, Pedon 6 has an isothermic rather than an isohyperthermic soil temperature regime.

Based on the crop requirements and the soil and land characteristics, a physical assessment of the soils of the study area was made for cassava, jojoba, and tomatoes. The evaluation showed that both rainfed cassava and jojoba were not suited in the study area. Irrigated tomatoes, however, were moderately suited at the lower elevation (Pedons 1 and 2), highly suited at the middle elevation (Pedons 3 through 5), and moderately suited at the higher elevation (Pedon 6).

Based on this study, it is concluded that:

1. Climate was the major influence on the formation of the Waiakoa and Keahua soils on Maui, Hawaii.

2. Parent material, as affected by erosion and deposition, was also very important in the formation of these soils.

3. In a mild climosequence of increasing rainfall and decreasing temperature, there was an increase in soil depth, clay content, soil acidity, and organic carbon content between the soils.

4. Rock fragments were common constituents in most of the soils of the study area, and their presence can be associated not only with erosion and deposition but also with exposure of weathering parent rock because of erosion.

5. Because of limited sampling, there is a need to examine the dominant soils of the study area and to verify the classification of the Mollisols of the Kihei-Waiakoa-Pulehu area.

6. Based on the crop requirements and the land and soil characteristics, the suggested land use for the study area is irrigated tomato production. Rainfed cassava and jojoba are not recommended.

APPENDIX

Soil profile descriptions

Pedon 1 (Elevation = 37 m, Rainfall = 250 mm).

Horizon	Description
Ap	0 to 26 cm; reddish brown (5YR 3/3) very cobbly silty clay loam; reddish brown (5YR 4/4) dry; moderate very fine granular structure; hard, friable, slightly sticky and slightly plastic; many very fine and fine roots; many very fine interstitial pores; 15 percent pebbles; 15 percent cobbles; 5 percent stones; slightly effervescent (hydrogen peroxide); neutral; clear wavy boundary.
Cr	26 to 52 cm; grayish brown (10YR 5/2) weathered rock with small amonuts of soil in fractures; white 10YR 8/2) dry; many very fine roots; moderately alkaline; clear wavy boundary.
R	26 to 80 cm; weathered rock; few very fine roots along fractures.

Pedon 2 (Elevation = 189 m, Rainfall = 360 mm).

Horizon	Description
Ap	0 to 5 cm; dark reddish brown (5YR 3/2) very stony silty clay loam; reddish brown (5YR 4/3) dry; moderate fine and very fine granular structure; hard, friable sticky and plastic; many very fine and few fine roots; many interstitial pores; 30 percent stones, 5 percent gravel; strong effervescence with hydrogen peroxide; neutral; clear smooth boundary.
AB	5 to 26 cm; dark reddish brown (5YR 3/2) stony silty clay loam; weak fine and medium subangular blocky structure; very friable, sticky and plastic; many very fine and fine roots; common very fine pores; 10 percent stones, 15 percent cobbles; strong effervescence with hydrogen peroxide; neutral; gradual smooth boundary.
BC	26 to 60 cm; dark brown (7.5YR 3/2) and dark reddish brown (5YR 3/3) silty clay loam; weak fine and medium subangular blocky structure; friable, sticky and plastic; common very fine and fine roots; many very fine and few fine pores; 30 percent soft weathered rock; slight effervescence with hydrogen peroxide; gradual irregular boundary.
Cr	60 to 72 cm; hard weathered rock with 15 percent unweathered rock.

Pedon 3 (Elevation = 366 m, Rainfall = 380 mm).

Horizon	Description
Ap1	0 to 10 cm; dark reddish brown (5YR 3/2); reddish brown (5YR 4/3) dry; moderate coarse and very coarse platy structure; hard, friable, slightly sticky and slightly plastic; many fine and common very fine roots; many very fine tubular pores; strongly effervescent with hydrogen peroxide; neutral; gradual wavy boundary.
Ap2	10 to 29 cm; dark reddish brown (5YR 3/2) silty clay loam; reddish brown (5YR 4/3) dry; hard, friable, slightly sticky and slightly plastic; many very fine and fine roots; many fery fine tubular pores; strongly effervescent with hydrogen peroxide; neutral; gradual amooth boundary.
Bw1	29 to 48 cm; dark reddish brown (5YR 3/3) silty clay loam; reddish brown (5YR 4/4) dry; weak fine and medium subangular blocky structure; hard, friable, slightly sticky and slightly plastic; many very fine and common fine roots; many very fine tubular pores; few pebbles; strongly efferverscent with hydrogen peroxide; neutral; gradual smooth boundary.
Bw2	48 to 82 cm; dark reddish brown (5YR 3/3) silty clay loam; reddish brown (5YR 4/4) dry; moderate fine and medium subangular blocky structure; hard, friable, slightly sticky and slightly plastic; many very fine and many fine roots; many very fine tubular pores; strongly effervescent with hydrigen peroxide; neutral; clear smooth boundary.
2Bw3	82 to 122 cm; dark brown (7.5YR and very dark brown (10YR 2/2) silty clay loam; brown (7.5YR 4/4) dry; strong very fine and fine subangular blocky structure; very hard, friable, slightly sticky and slightly plastic; common very fine roots; many very fine tubular pores; slightly efferverscent with hydrogen peroxide; neutral; gradual smooth boundary.
2Bw4	122 to 150 cm; very dark grayish brown (10YR 3/2) silty clay loam; grayish (10YR 5/2) dry; moderate very fine and fine subangular blocky structure; very hard; friable, sticky and plastic; few very fine roots; common very fine tubular pores; slightly effervescent with hydrogen peroxide; neutral.

Pedon 4 (Elevation = 503 m, Rainfall = 480 mm).

Horizon	Description
Ap	0 to 28 cm; dark reddish brown (5YR 3/2) silty clay; reddish brown (5YR 4/2) dry; massive parting to weak fine granular structure; very hard, firm, very sticky and very plastic; few fine and common very fine roots; many very fine tubular pores; few pebbles; slightly effervescent with hydrogen peroxide; slightly acid; abrupt smooth boundary.
Bw1	28 to 63 cm; dark reddish brown (5YR 3/2) silty clay; reddish brown (5YR 4/3) dry; weak coarse prismatic parting to weak fine and medium subangular blocky structure; very hard, firm, very sticky and very plastic; few very fine roots; common very fine tubular pores; common very fine dark concretions; violently effervescent with hydrogen peroxide; slightly acid; gradual wavy boundary.
Bw2	63 to 82 cm; dark reddish brown (5YR 3/2) silty clay; dark reddish gray (5YR 4/2) dry; weak coarse prismatic parting to strong very fine and fine subangular blocky structure; very hard, friable, very sticky and very plastic; few very fine roots; common very fine tubular pores; common very dark concretions; strongly effervescent with hydrogen peroxide; slightly acid; gradual wavy boundary.
Bw3	82 to 130 cm; dark reddish brown (5YR 3/2) silty clay; reddish brown (5YR 4/3) dry; strong very fine and fine angular blocky structure; very hard; friable; very sticky and very plastic; common non-intersecting slickensides; few very fine roots; many very fine tubular pores; common very dark concretions; strongly effervescent with hydrogen peroxide; neutral; clear wavy boundary.
Bw4	130 to 156 cm; dark reddish brown (5YR 3/2) silty clay; reddish brown (5YR 4/3) dry; moderate very fine and fine angular blocky structure; very hard, friable, very sticky and very plastic; common non-intersecting slickensides; few very fine roots; common very fine tubular pores; common very dark concretions; violently effervescent with hydrogen peroxide; neutral.

Pedon 5 (Elevation = 640 m, RF=500 mm)

Horizon	Description
Ap1	0 to 7 cm; dark brown (7.5YR 3/2) silty clay; dark brown (10YR 4/3) dry; strong very fine and fine granular structure; hard, firm, very sticky and very plastic; common very fine roots; many interstitial pores; few pebbles and cobbles; strong effervescence with hydrogen peroxide; neutral; gradual smooth boundary.
Ap2	7 to 29 cm; dark brown (7.5YR 3/2) silty clay; weak very fine granular structure with many clods; very hard, very firm, very sticky and very plastic; common very fine roots; many interstitial pores and few on the clods; common pebbles and few cobbles; strong effervescence with hydrogen peroxide; neutral; clear smooth boundary.
Bw	29 to 63 cm; dark reddish brown (5YR 3/2) silty clay; moderate fine and medium subangular blocky structure; friable, very sticky and very plastic; few very fine roots; many very fine pores; common stones; few cobbles and few pebbles; slight efferverscence with hydrogen peroxide; neutral; clear wavy boundary.
CB	63 to 97 cm; dark reddish brown (5YR 3/2) silty clay; moderate fine and medium subangular blocky structure; friable, very sticky and very plastic; few very fine roots; many very fine pores; few stones, few cobbles and common pebbles; slight effervescence with hydrogen peroxide; neutral; gradual wavy boundary.
C	97 to 150 cm; variegated very dark gray to dark brown (10YR 3/1, 3/2, 3/3) highly weathered rock that crushes to gravelly clay loam; firm, very sticky and plastic; common cobbles and stone-size rock cores; neutral.

Pedon 6 (Elevation = 732 m, Rainfall = 560 mm)

Horizon	Description
Ap	0 to 31 cm; dark brown (7.5YR 3/2) silty clay loam; dark brown (7.5YR 3/2) dry; moderate very fine and fine granular structure; hard, firm, slightly sticky and slightly plastic; many very fine and few fine roots; common very fine tubular pores; few cobbles; slightly effervescent with hydrogen peroxide; neutral; gradual smooth boundary.
Bw1	31 to 46 cm; dark brown (7.5YR 3/2) silt loam; dark brown (7.5YR 3/2) dry; weak very fine and fine subangular blocky structure; hard, friable, slightly sticky and slightly plastic; many very fine and few fine roots; common very fine tubular pores; few cobbles; slightly effervescent with hydrogen peroxide; neutral; gradual smooth boundary.
Bw2	46 to 58 cm; dark brown (7.5YR 3/2) silty clay loam; dark brown (7.5YR 3/2) dry; weak fine and medium subangular blocky structure; very hard, friable, sticky and plastic; many very fine roots; many very fine tubular pores; few pebbles; slightly acid; gradual wavy boundary.
Bw3	58 to 88 cm; dark brown (7.5YR 3/2) gravelly silty clay loam; dark brown (7.5YR 3/2) dry; moderate very fine and fine subangular blocky structure; very hard, friable, sticky and plastic; many very fine roots; many very fine tubular pores; common pebbles; medium acid; gradual wavy boundary.
B/C	88 to 160 cm; dark brown (7.5YR 3/2) gravelly silty clay loam; dark grayish brown (10YR 4/2) dry; weak very fine and fine subangular blocky structure; hard, friable, slightly sticky and slightly plastic; common very fine roots; many very fine tubular pores; common pebbles; medium acid.

LITERATURE CITED

Anderson, D.W., and E.A. Paul. 1984. Organo-mineral complexes and their study by radiocarbon dating. Soil Sci. Soc. Am. J. 48:298-303.

Asian Vegetable Research and Development Center (AVRD). 1982. 1981 Progress Report (AVRDC Publication 81-168). Shanhua, Taiwan, ROC.

Asian Vegetable Research and Development Center (AVRD). 1985. Progress Report, 1983. Shanhua, Taiwan, ROC.

Asian Vegetable Research and Development Center (AVRD). 1979. Proceedings of the 1st International Symposium on Tropical Tomato, Shanhua, Taiwan, ROC.

Birkeland, P.W. 1984. Soil and geomorphology. Oxford Univ. Press, New York.

Bohn, H.L., B.L. McNeal, G.A. O'Connor. 1979. Soil Chemistry. John Wiley & Sons, New York.

Brady, N.C. 1984. The nature and properties of soils. 9th ed., Macmillan Pub. Co., New York.

Buol, S.W., F.D. Hole and R.J. McCracken. 1980. Soil genesis and classification. Iowa State Univ. Press, Ames.

Cline, M.G. 1955. Soil survey. Territory of Hawaii. USDA, SCS, in cooperation with the Hawaii Agr. Exp. Sta. Series 1939, No.25. U.S Govt. Printing Office, Wash., D.C.

FAO. 1976. A framework for land evaluation. Soils Bulletin 32. FAO, Rome.

Fenton, T.E. 1983. Mollisols. In: L.P. Wilding, N.E. Smeck and G.F. Hall (ed.). Pedogensis and Soil Taxonomy. Elsevier, New York.

Foote, D.E., E.L. Hill, S. Nakamura, and G. Stephens. 1972. Soil survey of the Islands of Kauai, Oahu, Maui, Molokai, and Lanai, State of Hawaii. SCS, USDA, in cooperation with Univ. of Hawaii Agr. Expt. Sta., U.S. Govt. Printing Office, Wash., D.C.

George Jr, W.L., J.W. Scott and W.E. Splittstoesser. 1984. Parthenocarpy in tomato. In: J. Janick (ed). Horticultural Reviews. 6:65-84.

Gerrard, A.J. 1981. Soils and landforms; An integration of geomorphology and pedology.

Gould, W.A. 1983. Tomato production, processing and quality evaluation. 2nd ed. AVI Publishing Co., Westport, Connecticut.

Jenny, H. 1941. Factors of soil formation. McGraw-Hill Book Co., New York.

Juang, T.C. and G. Uehara. 1968. Mica genesis in Hawaiian soils. Soil Sci. Soc. of Am. Proc. 32:31-35.

Kononova, M.M. 1975. Humus of virgin and cultivated soils. In: J.E. Gieseking (ed.) Soil Components, Vol. 1, Springer-Verlag, New York.

Lal, R. 1980. Physical and mechanical characteristics of Alfisols and Ultisols, with particular reference to soils on the tropics. In: B.K.G. Theng (ed.). Soils with variable charge. Offset Publ., Palmerston North, New Zealand.

Macdonald, G.A., A.T. Abott, and F.C. Peterson. 1983. Volcanoes in the sea. The geology of Hawaii. Univ. of Hawaii Press, Honolulu.

Mittleider, J.R. 1981. Let's grow tomatoes. Horizon Publishers, Bountiful, Utah.

National Research Council. 1977. Jojoba. National Academy of Sciences. National Academy Press, Wash., D.C.

National Research Council. 1985. Jojoba: New crop for arid lands, new material for industry. National Academy Press, Wash., D.C.

Natural Vegetation Committee. 1973. Landscaping with native Arizona plants. University of Arizona Press, Tucson.

Paramanathan, S. and H. Eswaran. 1980. Morphological properties of Oxisols. In: B.K.G. Theng (ed). Soils with variable charge. pp35-43. Offset Publ., Palmerston North, New Zealand.

Porter, S.C. 1979. Hawaiian glacial ages. Quat. Res. 12: 161-187.

Porter, S.C., K. Pierce, and T. Hamilton. 1983. Late Wisconsin mountain glaciation in the western United States. In: S. Porter (ed.). Late quaternary environments in the United States. Univ. of Minnesota Press, Minneapolis.

Price, S. 1983. Climate, In: R.W. Armstrong (ed). Atlas of Hawaii. 2nd ed. pp 59-66. University of Hawaii, Honolulu.

Purseglove, J.W. 1974. Tropical crops: Dicotyledons. John Wiley & Sons, New York.

Ruhe, R.V. 1956. Landscape evolution in the High Ituri, Belgian Congo. Ser. Sci. 66. 108p. de l'INEA, Brussels.

Ruhe, R.V. 1964. An estimate of paleoclimate in Oahu, Hawaii. Amer. J. Sci. 262:183-193.

Ruhe, R.V. 1965. Relation of fluctuations of sea level to soil genesis in the Quaternary. Soil Sci. 99: 23-29.

Ruhe, R.V. 1975. Geomorphology; geomorphic processes and surficial geology. Houghton-Mifflin Co., Boston.

Ruhe, R.V., J.M. Williams, R.C. Shuman, and E.L. Hill. 1965. Nature of soil parent material in Ewa-Waipahu area, Oahu, Hawaii. Soil Sci. Soc. Am. Proc. 29: 282-287.

Schwertmann, U., E. Murad, and D.G. Schulze. 1982. Is there Holocene reddening (hematite formation) in soils of axeric temperate areas? Geoderma, 27:209-223.

Selling, O.H. 1948. Studies in Hawaiian pollen statistics, Part III on the late Quaternary history of the Hawaiian vegetation. Bernice P. Bishop Museum Spec. Publ. 39, Honolulu.

Simonson, R.W. 1962. Soil Classification in the United States. Science 37:1027-1034.

Smith, G.D. 1965. Lectures in soil classification. Pedologie: Special issue, no. 4. SCS, USDA. 1976. Soil survey laboratory data and descriptions for some soils of Hawaii. Soil Survey Investigation Report No. 29.

SCS, USDA in cooperation with Hawaii Agr. Expt. Sta. and Hawaiian Sugar Planters' Assoc. U.S. Govt. Printing Office, Wash. D.C.

SCS, USDA. 1984. Soil survey laboratory data and descriptions for some soils of MauiNet. SCS, USDA. in cooperation with Hawaii Institute of Tropical Agriculture and Human Resourses, Univ. of Hawaii, Honolulu.

SCS, USDA. 1984. Procedures for collecting soil samples and methods of soil analyses for soil survey. Soil Survey Investigation Report No. 1. US Govt. Printing Office, Wash. D.C..

Soil Survey Staff. 1951. Soil survey manual. USDA Agr. Handbook 18. U.S. Govt. Printing Office, Wash., D.C.

Soil Survey Staff. 1975. Soil Taxonomy. A basic system of soil classification for making and interpreting soil surveys. USDA Agr. Handbook 436. U.S. Govt. Printing Office, Wash., D.C.

Stearns, H.T. and G.A. Macdonald. 1942. Geology and ground-water resources of the Island of Maui. Div. of Hydrology, Territory of Hawaii.

Thomson, P.H. 1982. Jojoba handbook. Bonsall Publications, California.

Work, P. 1926. Tomato production. Orange Judd Publishing Co., New York.

Yermanos, D.M. 1979. Jojoba - a crop whose time has come. California Agriculture. Vol.33, No.7 and 8:4-7, 10-11.